ENGINEERING ANALYSIS

CAMERA SYSTEM, AERIAL RECONNAISSANCE

HIGH ACUITY, 18 x 18 INCH FORMAT, TYPE HR-244

This study was done to consider the available hardware components and techniques compatible with the requirements for a photographic reconnaissance system capable of obtaining small ground resolution (on the order of 1 foot) from altitudes between 80,000 and 120,000 feet at air speeds of Mach 0.9 to 3.0. The system is to be capable of providing "spot" coverage over a number of specific targets or to provide total coverage over a large area.

The study was to consider the current state-of-the-art in photographic systems in terms of the performance capabilities of the hardware components as they now exist and for the time period of two years. Particular attention was devoted to the possibilities inherent in the existing basic HR-248 Camera for upgrading, through the use of an improved high-acuity lens.

Attached is a specification and an outline drawing describing the proposed camera system resulting from this study. Following is a brief synopsis of the significant engineering analysis and computations performed in developing the specifications.

1. REQUIREMENTS

Altitude:	80,000 to 120,000 feet
Velocity:	Mach 0.9 to Mach 3.0
80,000 feet, Mach 0.9*	872 ft/sec
120,000 feet, Mach 0.9*	940 ft/sec
80,000 feet, Mach 3.0*	2910 ft/sec
120,000 feet, Mach 3.0*	3135 ft/sec
Rg (ground recognition):	1 foot on the ground over target area
Ø (angular resolution):	8.35×10^{-6} radians (minimum)
Film:	Thin-base, high resolution
Weight:	600 pounds, maximum
Volume:	Limited

2. LENS AND FOCAL LENGTH CONSIDERATIONS

Lens-film combination resolutions necessary to obtain a one-foot ground recognition at low contrast are listed below for lenses of several different focal lengths:

Lens focal length	24"	36"	48"	60"	72"
Required resolution (l/mm)	197	131	98	80	66

The largest lens focal length that can be accomodated in the available volume is 48 inches. To achieve a lens-film resolution of 100 lines per millimeter with a 48-inch focal length lens will require the use of high-resolution film, either SO-243, SO-213, or SO-130.

3. CAMERA TYPE

The two basic types of cameras considered for the 244 application were panoramic and framing. To use a panoramic camera and still attain the required transverse angular coverage, a short focal-length (24 inch or less) would be required. Because of the shape of the volume available, a longer focal-length (48 inch) folded-lens framing camera capable of wide transverse angular coverage can be more readily fit into the volume available. The tabulation below lists the angular coverage for different configurations and various focal lengths of panoramic and framing cameras:

Total Transverse Angular Coverage

	24" F. L.	36" F. L.	48" F. L.
Split Panoramic	120°	104°	-
Framing	230°	175°	140°

4. GROUND COVERAGE

The following tabulation lists the ground coverage available and assumes the use of a 9-inch wide format for the panoramic camera and an 18 x 18 inch format for the framing camera:

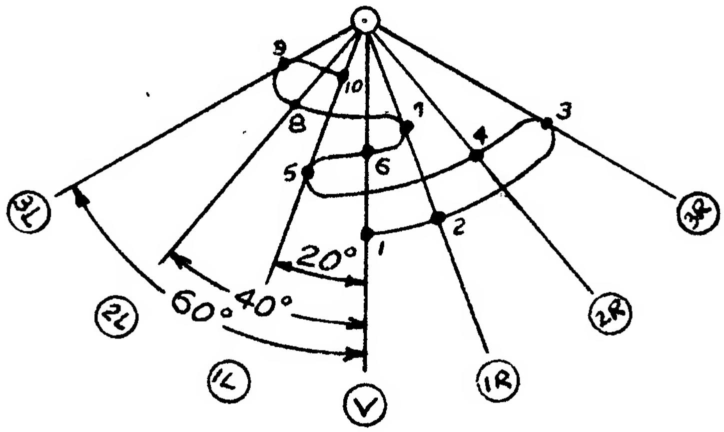
	Altitude	
	80, 000 feet	120, 000 feet
Split Panoramic (24"f. l.)	45 n. m.	68-1/2 n. m.
Framing (24" f. l.)	70 n. m.	105 n. m.

Because of the larger transverse angular-coverage capability, and the lower system resolution necessary to attain the required one-foot ground resolution, the 48-inch focal length folded-lens framing camera is recommended.

5. CAMERA CHARACTERISTICS

5.1 Cycle Rate. To attain the transverse angular coverage of 140°, the camera must take a vertical photograph and three oblique photographs on each

side of vertical, and do so in sufficient time to provide a minimum of 55 per cent forward overlap of all frames. The camera cycling sequence is indicated in the following diagram:



Required cycle rates for the seven-position mode at the two altitude extremes and two velocity extremes are tabulated below:

Required Cycle Rate, Seconds/Cycle

Altitude	Mach 0.9	Mach 3.0
80,000 feet	3.00 sec	0.87 sec
120,000 feet	4.45 sec	1.30 sec

Other combinations of oblique positions and modes of operation are available; however, cycle rates of these other modes will be longer than those shown in the preceding table.

5.2 IMC Rates. Image motion compensation rates over the range of altitudes and velocities will vary from 7.8 milliradians per second to 36.4 milliradians per second. IMC rate accuracy required to maintain the one-foot ground resolution figure will vary with shutter speed and IMC rate. Required IMC rate accuracies for various conditions of camera operation are listed below:

Shutter Speed, per sec	1/50	1/50	1/100	1/100
IMC Rate, per milliradian/sec	36	25	18	7.8
Required IMC Rate Accuracy	1.2%	1.6%	2.3%	5.3%

5.3 Types of IMC. Movement of the photographic image with respect to the film emulsion must be reduced to an acceptable limit during the exposure. Image motions are produced by vehicle forward velocity, vehicle stabilization errors, and vibration. Proper image motion compensation can be calculated for image motion produced by the vehicle forward velocity, with the accuracy determined by type of image motion compensation applied, accuracy of known parameters, degree of stabilization, and limits of vibration.

Image motion compensation is achieved by one of two means, the first of which is the effective movement of the film in the focal plane and, second, the effective rocking of the focal plane and optics. Several methods for achieving the above compensation are presently used in modern aerial cameras. Effective moving film compensation can be attained by actual translation of the film in the line-of-flight or by a lateral displacement of the lens in the line-of-flight. An effective rocking motion can be attained by actual rocking of the entire camera system, or by rotation of a viewing mirror. In rocking motion compensation, additional effects can be attained, dependent on the axis of rotation. The most desirable axis is a horizontal axis, parallel to the ground plane and perpendicular to the line-of-flight. The following discussion is based on the rocking-mirror IMC about an axis transverse to the line-of-flight and parallel to the ground plane.

5.3.1 Proposed IMC (Rocking Mirror). In the discussion of rocking film compensation, the first assumption will be based on the ideal system analysis ignoring stabilization, vibration, and accuracy of known parameters. These factors will be discussed in a later paragraph. A complete analysis has been made of the IMC by rotation about a transverse axis through the principal point on the optical axis. It can be shown that the error in the "X" in-flight direction is:

$$dx = \pm X^2 \frac{vt}{H^2}$$

where: dx = movement of a point in the "X" direction. The negative sign indicates that point moves in an opposite direction to the line-of-flight.

X = distance of the transverse axis in feet

v = velocity in feet/seconds

C = shutter speed in seconds

H = altitude in feet

The error in the "Y" transverse direction can be shown to be:

$$dy = \pm xy \frac{vt}{H^2}$$

where: dy = movement of a point in the "Y" transverse direction. A negative sign indicates a point aft that moves towards the line-of-flight, and a positive sign indicates a point forward that moves from the line-of-flight.

The resultant motion of an image is the vector sum of the movements in the "X" and "Y" directions.

$$\varepsilon_R = \sqrt{(xy)^2 + (x)^4}\left[\frac{vt}{H^2}\right]$$

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where: ϵ_R = resultant movement in feet
v = velocity in feet per second
t = shutter speed in seconds
H = altitude in feet
X = distance of point from transverse axis in feet
Y = distance of point from in-flight axis in feet

Figure 1 represents a plot of the ground resolution capability as a function of field of view. The resolution figure is based on movement of one bar width as defined by MIL-STD-150. The shaded area shown in each position format represents the area within a 100 line per millimeter capability. The velocity is assumed as 3,220 feet per second (Mach 3.0), altitude as 120,000 feet, and shutter speed as 1/250 second.

This shows that the vertical picture is compensated over the entire format for a 100 line per millimeter system with focal length of 48 inches and a format size of 18 x 18 inches. With 55 per cent overlap, a three-position mode provides full coverage within 100 lines per millimeter of total field of view. A seven-position mode provides almost full coverage within 100 lines per millimeter except for a small area in the far-oblique. Calculations show that this area has a better than 70-line-per-millimeter resolution.

5.4 Stabilization. To maintain a one-foot ground resolution, the camera will require a stabilized platform from which to operate. The stabilizer will have to be sufficient to maintain the stabilized pitch and roll rates to a value less than ± 0.3 milliradians per second.

The H-244 Stabilized Mount will steady the camera adequately to enable the operating photographic system to resolve an angle of 8 microradians at shutter speeds as low as 1/60 second. The mount will consist of a 3-axis flexure knuckle gimbal, three torquing motors, and vertical and one rate gyro (principal sensors). The electronic package will employ solid-state components in printed-board type construction.

The flexure knuckle will permit $\pm 3^{\circ}$ of freedom about each axis. This component was selected for high degree of reliability necessary in an inaccessible location, light weight, and for negligible maintenance requirements. No other type of mount has even been proven, under operating conditions, to fulfill the critical requirement for stability.

The remainder of the mount complement employs conventional design and will vary only in detail.

5.5 Shutter. To realize high light transmission efficiency and reliable operation, a two-curtain, focal plane shutter will be utilized.

A between-the-lens shutter was considered and subsequently rejected. The large lens aperture would require large shutter blades. At the higher shutter speeds, blade velocities would become quite high, as would the forces required to start and stop the shutter blades; consequently, a shutter of this type would

NOTES;

1) SHADED AREA [illegible] [illegible] RESOLUTION [illegible].

2) [illegible] AREA IN BETWEEN [illegible] SHADED AREAS ARE LESS THAN 100 LINES PER [illegible] BUT GREATER 70 LINES PER [illegible].

3) INFLIGHT AND TRANSVERSE DISTANCE ARE SHOW AS ANGULAR DISPLACEMENTS. THE

$$\tan^{-1} \frac{X}{H} = \theta_x \text{ (INFLIGHT)}$$

$$\tan^{-1} \frac{y}{H} = \theta_y \text{ (TRANSVERSE)}$$

1st OBLIQUE POSITION - 20°
2nd OBLIQUE POSITION - 40°
3rd OBLIQUE POSITION - 54°

ALTITUDE - 120,000 FT
VELOCITY - [illegible] FT/SECOND

SHUTTER [illegible] - 1/[illegible] SECOND
FOCAL LENGTH - [illegible] INCHES
FORMAT - [illegible] INCHES x [illegible] INCHES

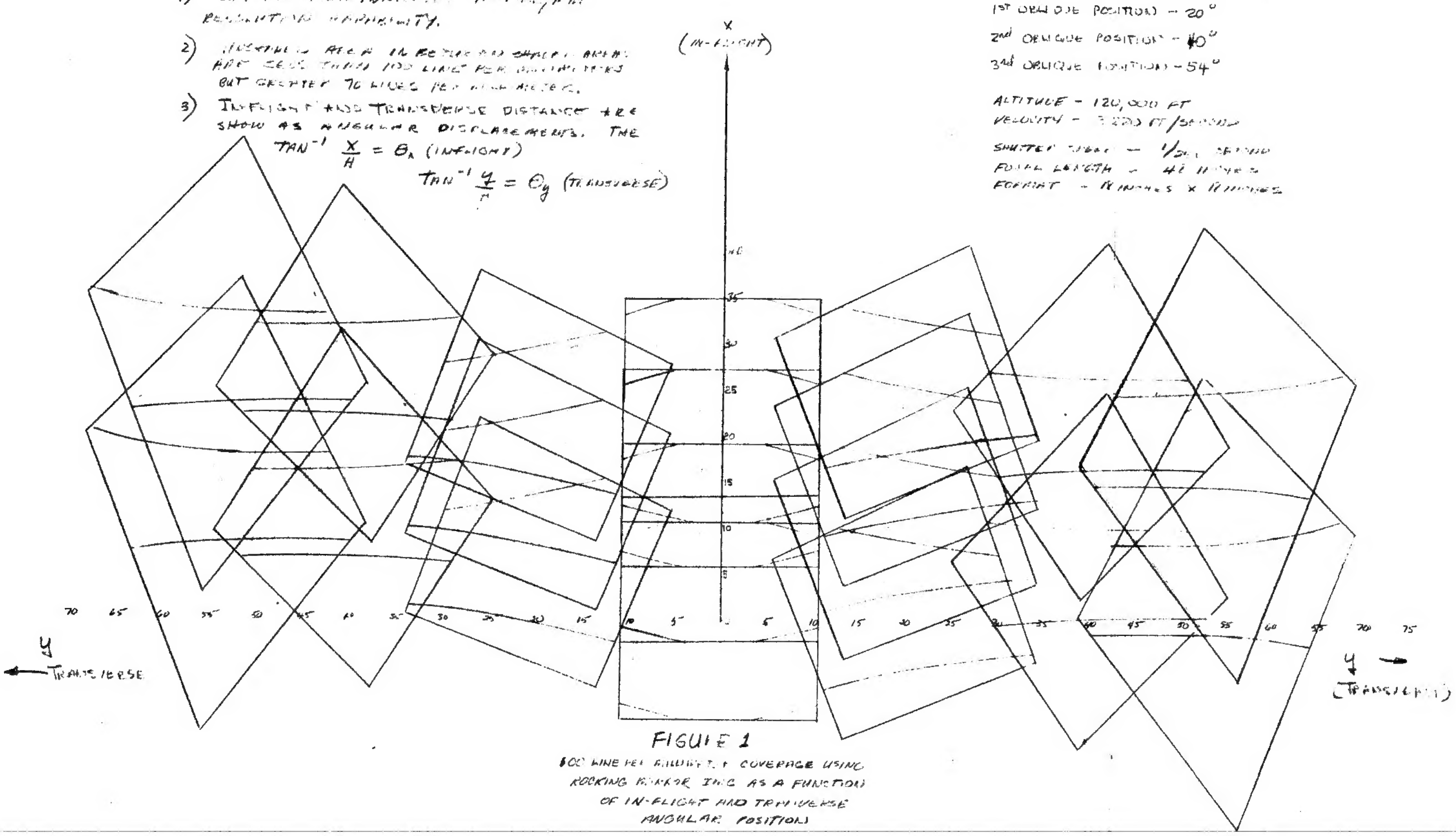

FIGURE 1

600 LINE PER MILLIMETER COVERAGE USING ROCKING [illegible] [illegible] AS A FUNCTION OF IN-FLIGHT AND TRANSVERSE ANGULAR POSITION

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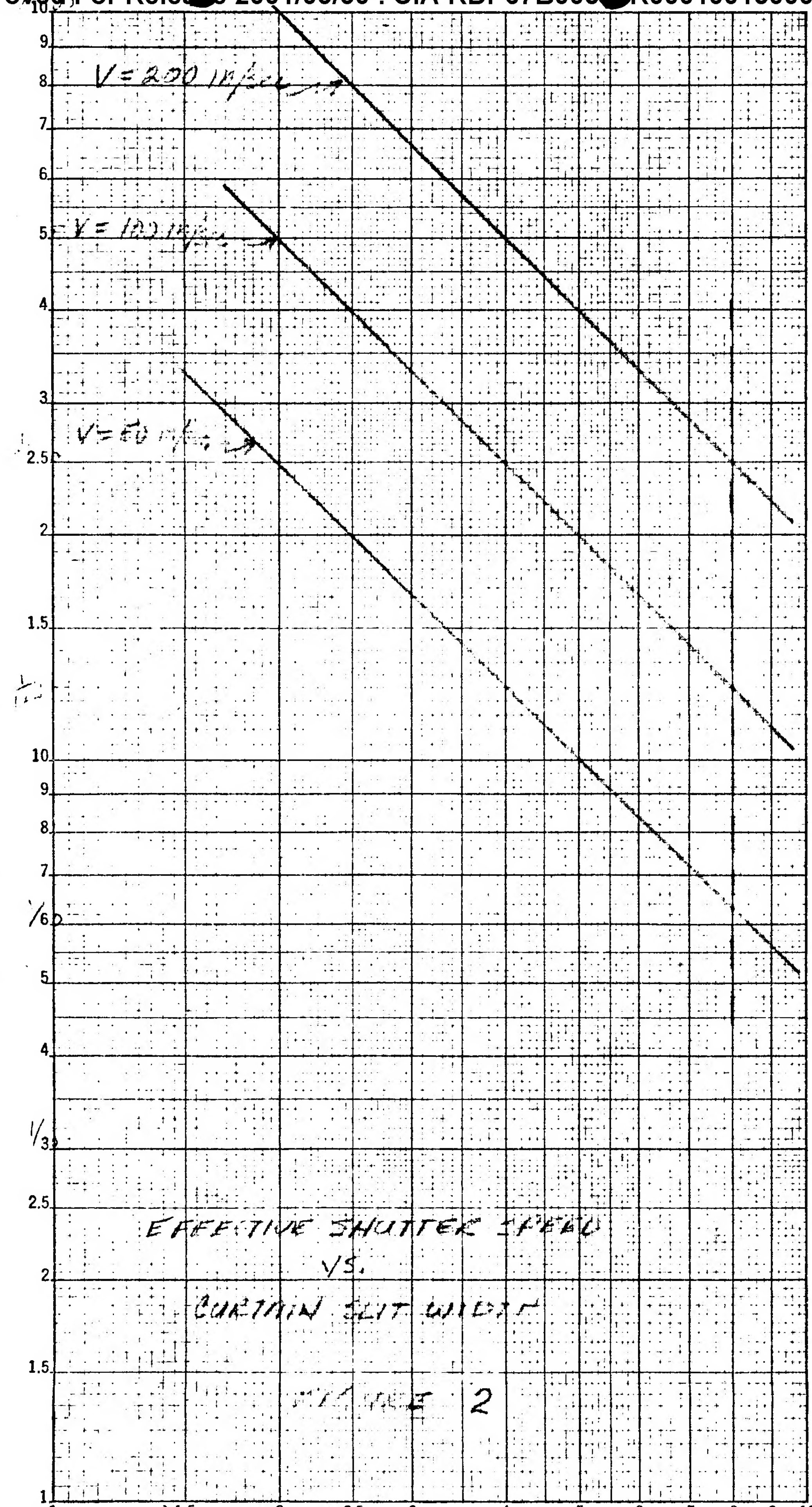
create considerable shock and vibration.

For this application, a focal plane shutter was felt to be a less complex, more reliable, and inherently a more versatile device. A wide range of shutter speed is available by varying either slit width or curtain speed. Because relatively slow curtain speeds may be used, shock and vibration forces will be smaller in magnitude and more readily subject to control and/or isolation.

For the proposed HR-244 focal plane shutter, it is anticipated that a broad range of shutter speeds, i.e., for winter as opposed to summer operation, will be set by means of a manual shutter slit-width adjustment prior to the mission. Variations within the broad range may be selected in flight and are achieved by changing curtain velocity. Figure 2 shows the shutter speed range for a typical winter mission. For a constant slit width of 0.8 inches (dashed vertical line), three different curtain speeds will provide effective shutter speeds of 1/60 second, 1/125 second, and 1/250 second.

Because the shutter curtain can be placed close to the focal plane, the light transmission efficiency of a focal plane shutter is inherently higher than that of a between-the-lens shutter. Shutter efficiency will vary with both effective shutter speed (slit width) and curtain distance from the focal plane. Figure 3 shows the variation in efficiency with shutter speed with the shutter curtain placed at two different distances from the focal plane.

5.6 Environment. The high resolution, 48-inch lens will have a very shallow depth of focus, in the order of ± 0.002 inch. Therefore, to maintain focus, the camera environment must be closely controlled. Environmental temperature variations cannot exceed ± 4°F. and pressure variations must be held to less than ± 4 mmHg. Figure 4 shows the allowable temperature and pressure variations. Although a temperature decrease would normally accompany a pressure decrease, if these two environmental factors are independently controlled, a situation could occur where pressure increased at the same time that temperature decreased. In this event, the errors would be additive, so it is desirable to control both temperature and pressure to tighter limits than shown on the curves of Figure 4.



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SLIT WIDTH, INCHES

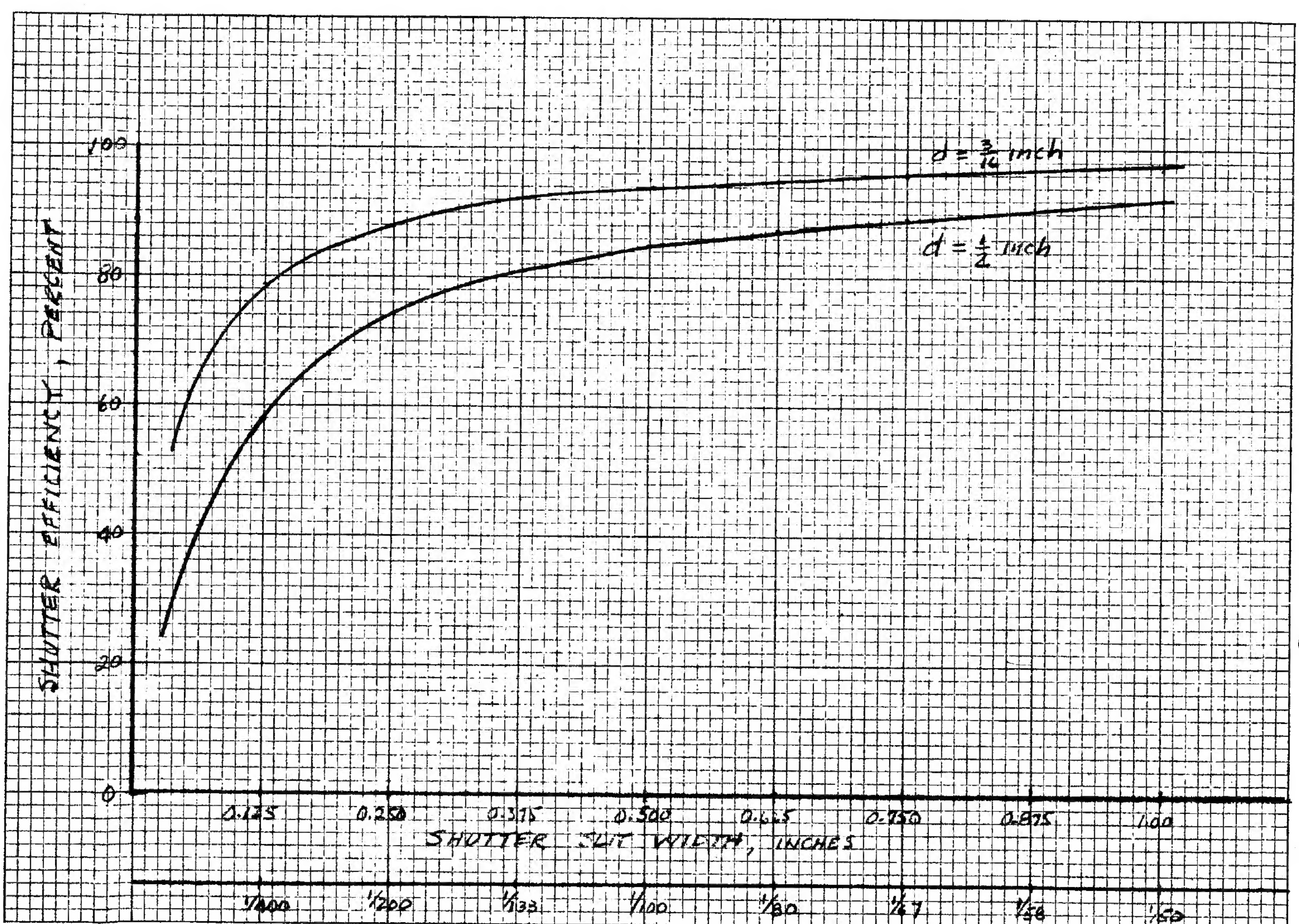

FIGURE 3 - SHUTTER EFFICIENCY VS. SHUTTER SPEED.

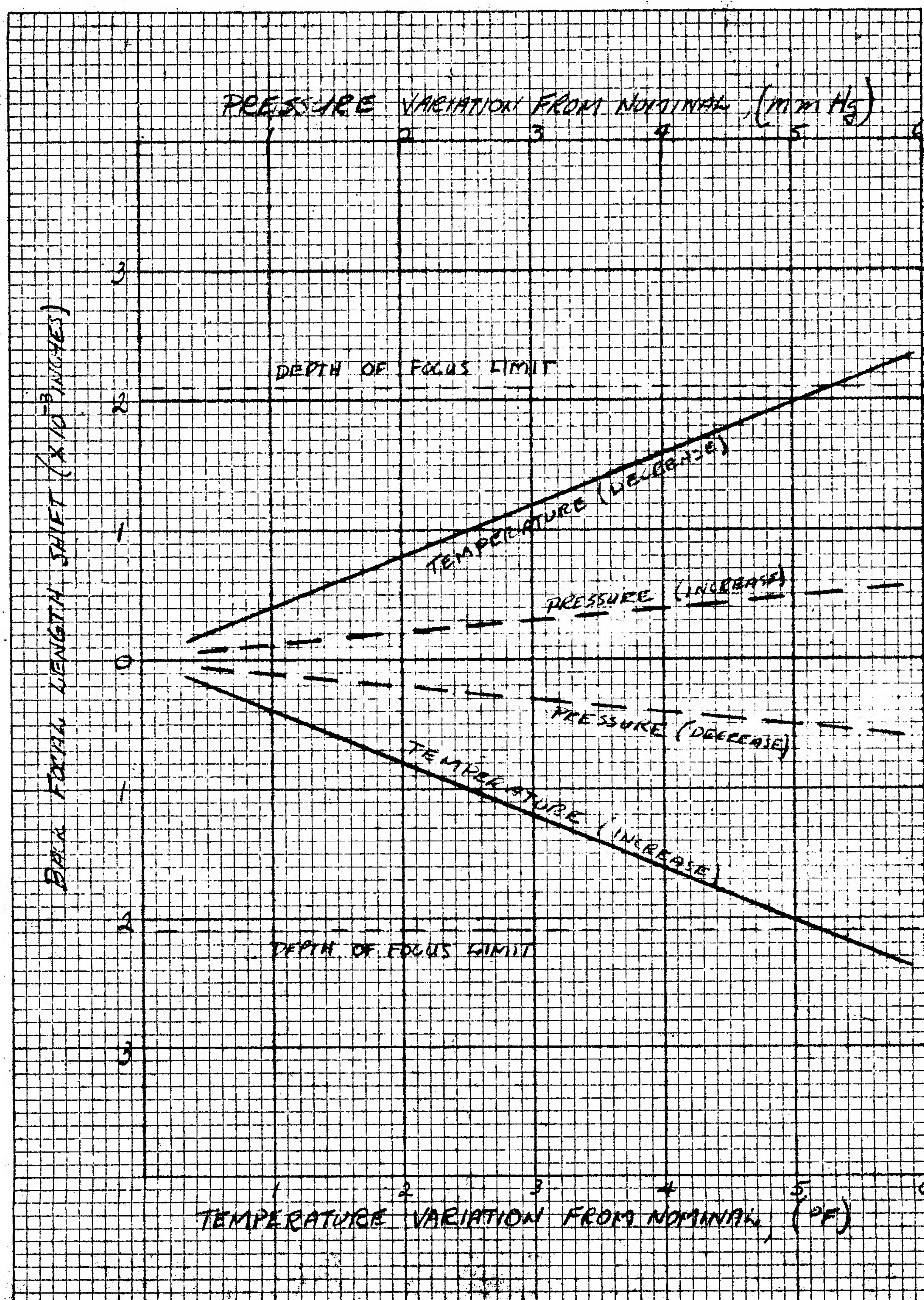

FIGURE 4 EFFECT OF TEMPERATURE & PRESSURE VARIATIONS